ABSTRACT: On the basis of experimental studies on the glaciers of the Polar Urals, Caucasus, and Pamir-Alai over the last decade, the peculiarities of solid precipitation accumulation in the glacial mountain zone are considered. Calculations of snow drifting and avalanche accumulation and their variability in time are given. It is found that the main mass of glaciers is situated in the zone of maximum precipitation. Snow drifting removes as much as 30-50 per cent of snow from open glaciers and, on the other hand, increases snow accumulation by 15 per cent on valley glaciers and more than doubles it on cirque and slope glaciers. The share of glacier nourishment by avalanches is one third of that by snow drifts. The differences of accumulation processes during winters of various snowfalls on the glaciers are shown. On the basis of the analysis made, a notion of a representative glacier is determined.

RESUME: La présente communication rend compte des irrégularités de l'accumulation des précipitations solides dans la zone glaciaire de régions montagneuses, durant la dernière décennie, sur les glaciers de l'Oural Polaire, du Caucase et du Pamir-Altai. Les résultats de calculs des accumulations de neige par tempêtes et avalanches et leurs variations sont mentionnés. On a trouvé que la masse principale des glaciers est située dans la zone de précipitations maximales. Les tempêtes balayent 30 à 50 pour cent de la neige déposée sur la surface des glaciers "ouverts" aux vents mais, par contre, elles augmentent de 15% l'accumulation des neiges sur les glaciers des vallées et de plus du double sur les glaciers des pentes et dans les cirques. Les neiges apportées sur les glaciers par les avalanches sont trois fois plus faibles que celles apportées par le vent. On donne les variations des accumulations de neige sur les glaciers selon des hivers inégalement neigeux. La notion du "glacier représentatif" est déduite des résultats de cette étude.

Glacier mass balance, as it is known, is the result of two processes, accumulation and ablation. At present we have at our disposal a number of direct methods of measurement and indirect calculation of surface ablation. But at the same time, direct accumulation measurements are difficult to make due to the limited efficiency of the equipment used, such as precipitation gauges and snow drift gauges. The indirect accumulation calculations are not accurate enough because accumulation is determined not only by the amount of solid precipitation but by the input of snow drift and by avalanche nourishment related to activity of other factors.

A great deal of research on the process of accumulation has been carried out in the USSR on the glaciers of the Polar Urals, Caucasus, and Pamir-Alai. In this paper some general conclusions of these studies in the selected mountain glacier basins where investigations are being made under IHD are described.
RELATION OF GLACIERS WITH THE MAXIMUM PRECIPITATION BELT

The investigations of glacier regions of the USSR show that most glaciers are located near the belt of maximum precipitation (on a given mountain range). This maximum is determined on one hand by the general regularity of the solid precipitation increase up to a definite elevation, and on the other by wind redistribution of snow.

The level of maximum precipitation, as a rule, is located fairly close to the glacier equilibrium line, and annual sums of precipitation are great even under the conditions of the so-called continental climate. According to our data the increase of precipitation on Elbrus is observed up to a height of 4000 m asl where yearly about 1500 mm of precipitation falls. In Central Pamir (region of the Fedchenko Glacier), the level of maximum precipitation (about 1500 mm) is at an elevation of about 4500 m, and in East Pamir at an elevation of 5000-5500 m asl, there is about 800-1000 mm of precipitation; at the same time in the valley of Lake Kara-Kul' (3914 m) only 70 mm of precipitation falls per year. These figures are evidence of a great accumulation intensity on temperate mountain glaciers.

Snow available for redistribution is transported by the wind in the atmosphere when suspended particles find themselves in a strongly directed flow of air. At this moment two processes are of great significance [1]: local increase in the amount of solid precipitation at an intensification of rising air currents and redistribution of precipitation in the field of curvilinear air currents. The activity of both processes is caused by powerful rising air currents on the slopes of ranges exposed to the main flow of moisture, which is why observations are better when mountain ranges are perpendicular to the main direction of air mass flows carrying moisture. Snow precipitation is dispersed by winds and consequently causes formation of an intensive snow accumulation zone stretching some kilometres on the lee slopes of the ranges. In the Polar Urals zones 12-15 km in length are observed. They are found in the Altai, Caucasus. As a result the maximum precipitation belt where most glaciers locate appears on lee and windward slopes of a mountain range.

SNOW AND AVALANCHE GLACIER NOURISHMENT

Snow drifting, that is transport of snow raised from the surface by wind, has a very different significance in the process of accumulation. It is characterized by a distance of snow transport (L), the average distance a separate snow particle is transported. The calculation L by the formula

\[ L = \frac{\Sigma Q_T}{X_S - \Delta H} \]

where \( \Sigma Q_T \) = amount of snow transported by wind at a given period of time, \( X_S \) = amount of solid precipitation at the same time, \( \Delta H \) = snow mass increase at a given time, showed that the distance of snow transport on mountain glaciers was small: it does not exceed 0.5 km and often decreases to 100 m. It is small due to the roughness of the relief, which detains the snow transport and retains
most of the snow in the depressions encountered along the way.

Snow transport operates over small distances only and snow is not transported over mountain ranges. In the mountains due to the great unevenness, there is no plane surface over which the air currents could saturate with snow and the roughness of the relief causes snow to fall from the current. The snow-wind current is not sufficiently saturated, and at the same velocities varies the amount of snow transported. This results in a very uneven snow accumulation.

Mountain glaciers are split into two groups according to the intensity of snow drift activity. The first group comprises glaciers situated on open lee slopes: glaciers of volcanic cones and glaciers of flat summits. Here mean annual velocities of wind can be 6-8 m/sec and snow drifts occur 150-170 days a year. On such glaciers observations in the Altai [2] and Tien-Shan [3] prove that half the accumulated snow is blown off.

Valley and cirque-valley glaciers encircled by high mountain slopes constitute a second group. In the accumulation areas of such glaciers strong winds seldom occur: mean annual wind velocities do not exceed 3 m/sec. These glaciers receive additional nourishment from snow drift transport from the surrounding slopes, neighbouring summits, and plateaux. In the accumulation area of average valley glaciers snow drift concentration accounts for about 15 per cent of the annual precipitation.

The share of snow drift in the nourishment of cirque and slope glaciers is much greater. In some cases the volume of snow brought by snow drifting is much greater than all solid precipitation on the glaciers. Thus where annual precipitation is 600-800 mm in the region of present-day glaciation in the Polar Urals the cirque glaciers receive, mainly by snow drifting, an annual snow accumulation of 200-400 g/cm² [1].

Snow drift nourishment of glaciers is sometimes difficult to distinguish from avalanche nourishment. The value of the latter can be judged by the dimensions of avalanche snow banks. The area of such banks can be 10,000 to 50,000 m², their volume (at an average thickness of 20 m) 200,000 to 1,000,000 m³, and their mass 100,000 to 500,000 tons. Where a cirque glacier 1 km² in size is considered, it comprises an increase of snow storage by 1-5 g/cm² which should be acknowledged as considerable.

K.S. Losev's calculations [4] and our estimations (see Table 1) show that avalanche drift from slopes constitutes, on the average, about 10 per cent of maximum snow storage (variations from 1 to 30 per cent). From this we conclude that the input of avalanche nourishment in the total accumulation of valley glaciers, as a rule, does not exceed 10 per cent and seldom reaches 20 per cent (on the average it equals 5 per cent). On small glaciers the avalanches constitute up to 40 per cent of the total volume of accumulated solid precipitation (on the average 20 per cent) and under particularly favourable conditions this figure may exceed 100 per cent. All the given figures are at least three times less than the share of snow drifts.

The input of snow drift and avalanche nourishment usually differs for glaciers of different morphological types as expressed by the values of the glacier coefficient (K) - ratio of accumulation and ablation areas. It is clear that the higher K is, the less snow concentration in the accumulation area of glaciers there is. The results of our studies in two small basins of the Alai Range [5] show that the slope and hanging glaciers bore the highest glacier
Table 1

Input of Avalanche Nourishment as % of Total Accumulation of Glaciers (percentage of the sum of precipitation)

<table>
<thead>
<tr>
<th>Snow drift by avalanches from slopes, % from maximum snow storage</th>
<th>Big valley glaciers</th>
<th>Small cirque-valley and cirque glaciers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.04-0.8</td>
<td>0.4-0.5</td>
</tr>
<tr>
<td>10</td>
<td>0.4-8</td>
<td>4.3-45</td>
</tr>
<tr>
<td>20</td>
<td>0.8-16</td>
<td>8.6-90</td>
</tr>
<tr>
<td>30</td>
<td>1.2-24</td>
<td>13-135</td>
</tr>
</tbody>
</table>

coefficient (K = 2-2.5): the first due to the complete absence of, or very low, snow concentration on its surface, and the second due to frequent breaking-off of snouts hanging on steep slopes. Cirque glaciers have the least glacier coefficients (K = 1.4-1.5) because of maximum snow concentration and that is why they are to be found on the lee side of lateral ranges to which the highest amount of snow drift is transported and which causes avalanches. In the region considered, valley glaciers have the closest coefficient to the average (K = 1.6-1.7), which is evidence of average conditions in nourishment and regime.

VARIABILITY OF THE MAIN ACCUMULATION COMPONENTS

There are two main factors determining snow accumulation on glaciers - amount of precipitation and wind velocity. The first factor is much less variable than the latter. This is why variations of snow drift readings from year to year depend mainly on variability of precipitation. As a rule, with increase in solid precipitation, intensity and duration of snow drift transport increase even at stable mean winter wind velocities. The latter is explained not only by the fact that with the increase of precipitation the discharge of snow drift grows, but mainly because with additional input of snow into the wind current from clouds, the critical wind velocity, at which drifting commences, becomes less. Less frequently the increase of snow transport duration can be related to a slight rise in winds accompanying snowfalls.

However the dependence of snow drift transport volume on the amount of solid precipitation is far from a simple proportion and the changes of these two values never occur at the same time. This is because the changes in the winter regime of those glaciers where accumulation mainly depends on snow drifts can not be synchronous with changes in the regime of the glaciers where accumulation depends on the total amount of precipitation. These differences can be so great that they lead to various changes in time of mass balance of such glaciers.

Those glaciers with considerable snow drift and avalanche nourishment, as a rule, have a more variable accumulation from year to year than the glaciers where local factors are of no significance. Total accumulation on the latter glaciers varies from year to year in proportion to variations in total precipitation. On cirque glaciers where nourishment is predominantly by snow drift and avalanche, annual variations of total accumulation are mainly due to
duration and intensity of snow drift and can be great. Thus on the
Obruchev Glacier (Polar Urals) the input of snow drift in 1957-1958
was 50 g/cm², and in 1959-60, 170 g/cm² [1].

The program of our studies on Elbrus [6] included observations
of snow accumulation on the glacier during the abnormally snowy
winter of 1962-63. Later it was possible to compare these observa-
tions with data obtained in this region during the winters of 1957-
58, 1958-59, and 1961-62, with weather conditions close to the aver-
age [7]. In the winter of 1962-63 the amount of precipitation ex-
ceeded the mean value twice over whereas air temperature and wind
velocity differed from the winter average only very slightly (by
1° and 0.7 m/sec). However changes in the accumulation regime on
the glacier were great.

As a result of these studies we were able to establish duration
and intensity of general snow drift as the main factor of accumula-
tion on open mountain glaciers. During snowy winters the percentage
of general snow drift increases and it leads to the growth in the
amount of snow transported (114,000 tons versus 70,000-75,000 tons
in other years). At the same time wind erosion during snowy winters
sharply decreases (7-8 per cent versus 20-30 per cent in usual years)
because of decrease in duration and strength of blowing snow drifts.
This serves to preserve precipitation on the glacier, as it is an
additional factor of accumulation.

During abnormally snowy winters snow blows on the glacier for a
much shorter time (400 hours versus 600-800 hours in usual years)
because constant and strong general snow drifts lead to a consider-
able packing of snow (density of the surface snow layer is 0.30 g/cm³
versus usual 0.23 g/cm³) which hardly yields to wind erosion. During
snowy winters snow accumulation on the glacier is greater than usual
as, under the predominance of general snow drifts during such years,
the snow-wind current is saturated mainly by falling snow but not by
accumulated snow.

These conclusions concern only the glaciers that are nourished
by precipitation. Evidently, on small glaciers, where snow drifts
play a great part in the nourishment, the accumulation may increase
even during winters of average snowfall but with greater frequency
of snow drifts.

A further task of studies in this field must be a production of
quantitative characteristics of input of separate components in the
nourishment of glaciers as functions of their sizes and morphology,
as well as of the main meteorological factors of the accumulation
period. These studies are being made now within the frameworks of
comprehensive investigations of ice, water, and heat balance on
selected glacier basins under the IHD program. They will be of
considerable help in defining a representative glacier. In my opin-
ion a representative glacier is one nourished basically by atmospher-
ic precipitation (but not by snow drift and avalanche snow transport).
Our preliminary studies show that valley or cirque-valley glaciers
of average (for a given mountain region) size with well-developed
accumulation and ablation areas should be considered as represen-
tative.

REFERENCES

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398


DISCUSSION

F. Müller (Switzerland) - Dr. Kotlyakov's paper on the parameters affecting the snow accumulation in a glacierized basin was most interesting as we have attempted, over the last few years, to employ a quantitative approach to the same problem. A statistical model based on several morphometric parameters (elevation above sea level, exposure, slope, three scales of surface roughness) was developed in our group and tested by G. Young in a small high Arctic watershed on Axel Heiberg Island, N.W.T., and on Peyto Glacier in the Rocky Mountains of Canada. Triangular and 100 m-square grids were used for the field measurements and for the numerical computations. A computer mapping program permits easy presentation of the results. Thus areal distribution and total snow quantities in the basin can be assessed faster and more accurately than with conventional techniques.

V.M. Kotlyakov (U.S.S.R.) - Yes, we have also made some studies of this type in the Northern Urals.

M.R. de Quervain (Switzerland) - With respect to the nourishment of glaciers by avalanches as compared to that by snow drift, it should be stressed that avalanches do not bring in snow from areas outside the watershed of a glacier as snow drift does in many cases. The role of the avalanches is particularly important in concentrating snow masses, thus protecting a glacier from ablation (melt and evap-
oration). If avalanches do not occur above the snow line, tributary glaciers (hanging glaciers, etc.) are formed as is often observed.